Final Report

"Design of the Bleed Slot for the Purdue University Mach 6 Tunnel"

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14. ABSTRACT
The research focused on the computational redesign of the shape of the bleed slot for the Purdue University Mach~6 wind tunnel to eliminate the axisymmetric separation bubble believed to exist on the inner surface of the bleed slot lip. This separation bubble is considered the most likely cause of the early transition of the boundary layers from laminar to turbulent conditions on the test section walls. This early transition, in turn, was deemed responsible for the high noise level in the tunnel at driver tube stagnation pressures above approximately 9 psia (61.8~kPa) as of September 2004, and precluded the quiet operation of the tunnel at high Reynolds number (high stagnation pressure). A successful redesign of the shape of the bleed slot was achieved. No separation bubble was observed in detailed Navier-Stokes simulations at stagnation pressures up to 300 psia.

15. SUBJECT TERMS
Transition, Boundary layers, hypersonic flow, computational fluid dynamics, aerodynamic design

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Abstract

The research focused on the computational redesign of the shape of the bleed slot for the Purdue University Mach 6 wind tunnel to eliminate the axisymmetric separation bubble believed to exist on the bleed flow and main flow sides of the bleed slot lip. This separation bubble is considered the most likely cause of the early transition of the boundary layers from laminar to turbulent conditions on the test section walls. This early transition, in turn, was deemed responsible for the high noise level in the tunnel at driver tube stagnation pressures above approximately 9 psia (61.8 kPa) as of September 2004 (using the original electroformed nozzle), and precluded the quiet operation of the tunnel at high Reynolds number (high stagnation pressure).

A successful redesign of the shape of the bleed slot was achieved. No separation bubble was observed in detailed Navier-Stokes simulations at stagnation pressures up to 300 psia. The redesigned bleed slot coordinates have been provided to Purdue University, and a remachining of the electroformed nozzle to the new shape is planned.

1. INTRODUCTION

The accurate prediction of boundary layer transition at hypersonic speeds is essential to the development of effective hypersonic military air vehicles, as the location and extent of the region of transition affects the overall vehicle drag and thermal load. Existing methods for prediction of transition (*e.g.*, the e^N method [Malik 1990]) are not sufficiently accurate, nor do they account for the wide variety of physical factors affecting the transition process. Morever, a full understanding of the physical processes causing hypersonic transition (*e.g.*, freestream disturbances, surface waviness and roughness) is lacking (Schneider 2001a). Previous hypersonic vehicle designs have been adversely affected by the inaccurate modeling hypersonic transition (see Schneider 1998a).

2. PURDUE UNIVERSITY MACH 6 TUNNEL

The Purdue University Boeing/AFOSR Mach 6 Quiet Tunnel (Fig. 1) was designed by Prof. Steven Schneider (Purdue University) to provide a state-of-the-art facility for investigation of laminar to turbulent transition at hypersonic speeds (Schneider 1998a, Schneider 1998b). The tunnel is a Ludwieg tube design (Schneider 1995). The principle objective of the tunnel is (Schneider 1998a):

> "The quiet tunnel is designed to stabilize the highly symmetric flow on an axisymmetric nozzle wall in order to delay nozzle-wall transition long enough to maintain quiet flow over an asymmetric model all the way to natural transition".

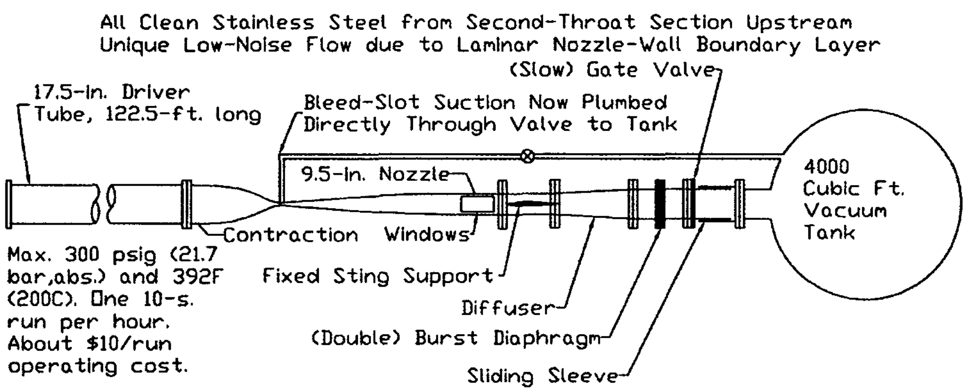

Fig. 1 Boeing/AFOSR Mach 6 Quiet Tunnel (Schneider 2000b)

Based upon a detailed survey of existing flight transition data (Schneider 1998a), Schneider concluded that the tunnel should have a test zone[†] Reynolds number up to $Re_L = 30 \times 10^6$. This represents an order of magnitude improvement over the established maximum quiet flow Reynolds number of the now-decomissioned Langley Mach 6 Quiet Tunnel. Based upon budgetary and other considerations, a Mach 6 tunnel with a 9.5 inch diameter test section was designed and constructed with a nominal design total pressure $p_{t_\infty} = 150$ psia (1.03 MPa) and total temperature $T_{t_\infty} = 440$ K to 456 K (Schneider 1998b, Schneider 2000b). The estimated maximum test flow Reynolds number (at the design conditions) is $Re_L = 4.8 \times 10^6$ based upon e^N analysis with $N = 7.5$ (Schneider 2000b) and a model length of 47.5 cm (18.686 in) as indicated in Fig. 2.

† Based upon the length of the front cone of the back-to-back cones that form the quiet zone.

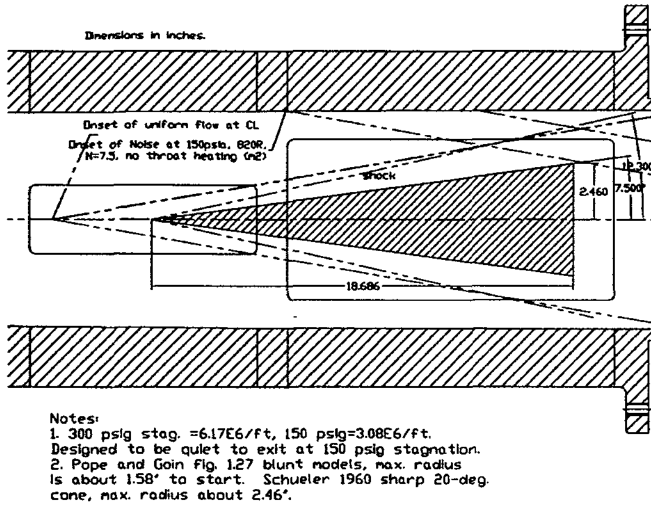

Fig. 2 Test section with model (Schneider 2000b)

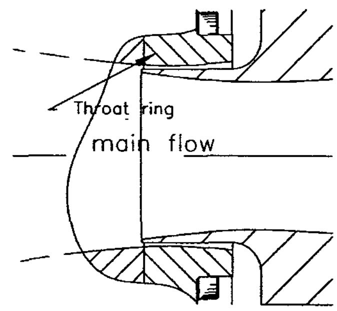

Fig. 3 Original bleed slot (Schneider *et al* 2002a)

An axisymmetric bleed slot (Fig. 3) is incorporated just upstream of the nozzle throat to remove the boundary layer that develops in the driver tube, thus eliminating the possibility that residual disturbances from the driver tube boundary layer might cause earlier transition on the nozzle wall. The nozzle wall boundary layer thus begins at the stagnation point on the bleed slot lip. The initial bleed slot design was based upon the 1-D inviscid streamtube analysis used by Beckwith (Alcenius *et al* 1994). The shape of the bleed slot flow is critically important since it determines the position of the stagnation point on the bleed lip (Schneider 1998b).

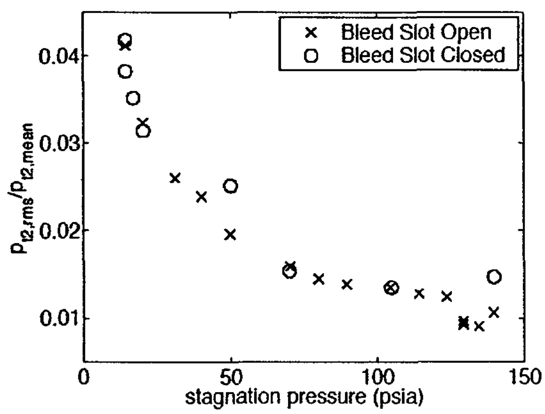

Fig. 4 RMS pitot pressure

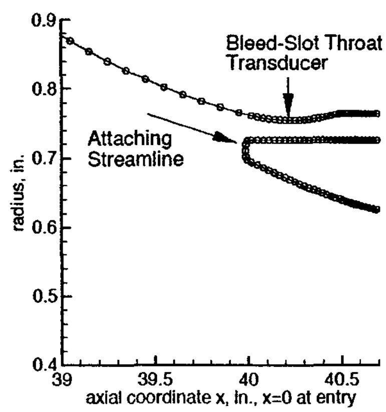

Fig. 5 Bleed slot

Mean and fluctuating pitot pressure were measured in the nozzle test section using Kulite fast pressure transducers (Schneider and Skoch 2001b). The relative rms fluctuation level is shown in Fig. 4 as a function of the stagnation pressure. The minimum relative rms level is approximately 1% which is an order of magnitude larger than the nominal maximum permitted value for quiet flow (*i.e.*, 0.1%). The principal cause of the noise was considered to be unsteadiness in the region of the bleed slot due to the location of the stgnation point on the separation streamline (Fig. 5). If the separation streamline stagnates at a location too far above or below the nosetip of the bleed slot, a separation bubble can form. The separation bubble can cause unsteadiness that feeds into the nozzle boundary layer resulting in earlier transition of the nozzle boundary layer.

Schneider *et al* (2002a) evaluated five different bleed slot designs. A modest improvement in the noise level (Fig. 6) was obtained at the highest stagnation pressures; however, the minimum level (0.5%) was still a factor of five too high for quiet flow. A sixth bleed slot design was evaluated and achieved quiet flow at low stagnation pressures (Fig. 7); however, the corresponding Reynolds number is too low for evaluation of transition to turbulence on a model in the test section.

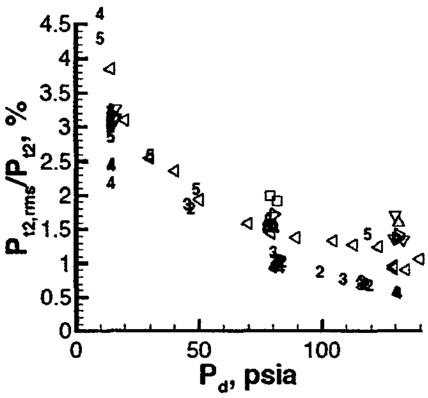

Fig. 6 RMS pitot pressure
(see Schneider *et al* 2002a for legend)

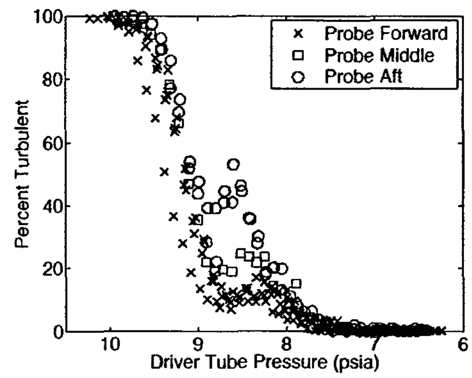

Fig. 7 Intermittency (Bleed Slot Design No. 6)
(Schneider *et al* 2002b)

A seventh bleed slot design (Fig. 8), denoted Model 7, was evaluated by Schneider *et al* (2003a) based upon a one-dimensional inviscid analysis. The rms relative pitot pressure still exceeded the maximum allowable level for quiet flow operation (Fig. 9). Subsequently, the centerbody wedge (*i.e.*, second throat) was removed and the tunnel quality was improved significantly at low stagnation pressures (Fig. 10) (Schneider *et al* 2003b); however, the range of quiet flow remained at $p_{t_\infty} \leq 8$ psia (Fig. 11). Additional experimental studies have been conducted (Schneider *et al* 2004a, 2004b) to further understand the cause of the tunnel noise. Schneider concluded (Schneider *et al* 2004b) that fluctuations generated at the nozzle throat due to problems with the bleed slot flow are a likely cause.

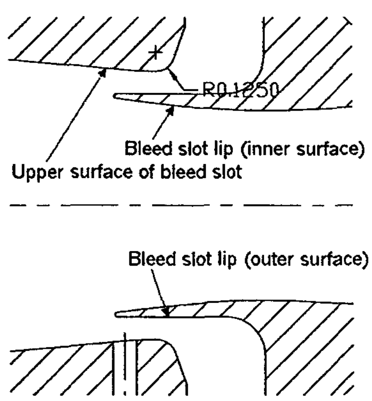

Fig. 8 Bleed slot design no. 7
(Schneider *et al* 2003a)

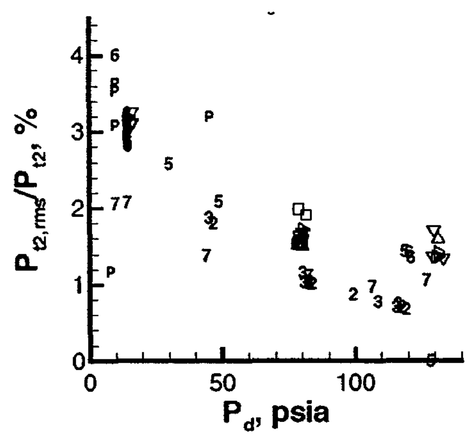

Fig. 9 RMS pitot pressure
(see Schneider *et al* 2003a for legend)

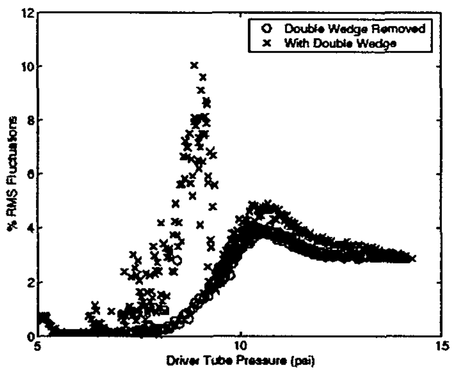

Fig. 10 RMS pitot pressure
(Schneider *et al* 2003b)

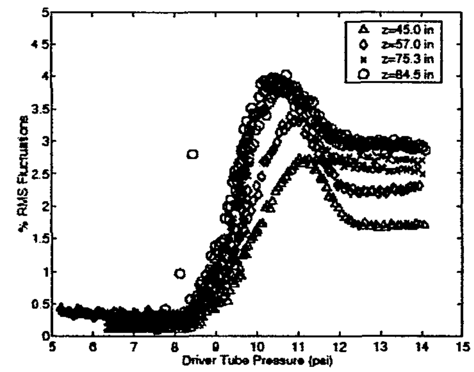

Fig. 11 RMS pitot pressure
(Schneider *et al* 2003b)

3. RESULTS

3.1 Configuration

The bleed slot configuration selected for redesign was Model 7 (see above) based upon discussions with Prof. Steve Schneider. Detailed Navier-Stokes simulations (Taskinoglu *et al* 2005) and Selin Aradag (Aradag *et al* 2006) revealed separation bubbles on the bleed flow and main flow sides of the bleed lip immediately downstream of the stagnation point at stagnation pressures above approximately 9 psia. The redesign focused on reshaping the bleed slot lip in the vicinity of the stagnation point to eliminate the separation bubbles at stagnation pressures up to 300 psia.

3.2 Methodology

Numerical simulations were performed using the structured multi-block CFD solver GASPex Version 4.1.2. The model equations are the laminar, compressible Navier Stokes equations. The inviscid fluxes are discretized using Roe's Method (3rd order) with Harten correction. The flux limiter is Min-Mod. The inflow boundary condition is a characteristics-based Riemann subsonic inflow condition. The forced outflow boundary condition for the bleed slot and nozzle exits. An adiabatic, no-slip condition is applied to the solid boundaries. An implicit dual-time stepping method was utilized to achieve time-accurate simulations. The total simulation time was taken to be four times the time necessary for the flow to go from the bleed lip to the exit of the computational domain, corresponding to 1.1 milliseconds.

3.3 Redesign of Bleed Slot Lip

A variety of redesigns of the bleed slot lip were performed (Aradag *et al* 2006) that modified the geometry within the first several millimeters. The final design (denoted Lip 8) achieved complete elimination of the separation bubbles on both the bleed flow and main flow sides of the lip up to 300 psia. The geometry is shown in Fig. 12. This geometry was obtained using four different cubic splines. Also, in order to remove the scratches on the actual nozzle lip surface, the tip point of the lip was moved 0.005 in downstream.

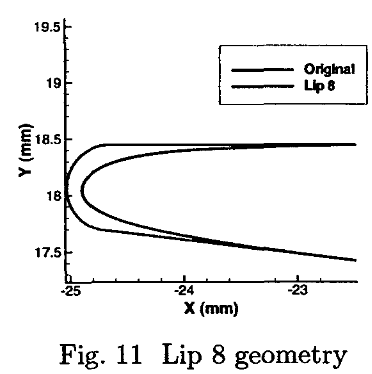

Fig. 11 Lip 8 geometry

Steady and unsteady computations were performed on Lip 8 geometry for three different pressures 50, 150 psi and 300 psi, at a stagnation temperature of 433 K. The Mach number contours for the steady simulations of Lip 8 at 150 psi and 300 psi are shown in Fig. 12 and Fig. 13, respectively. The separation bubbles on both the lower and upper parts of the bleed lip are eliminated.

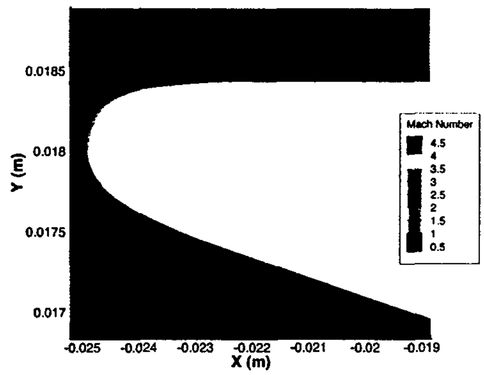

Fig. 12 Mach number contours (150 psia)

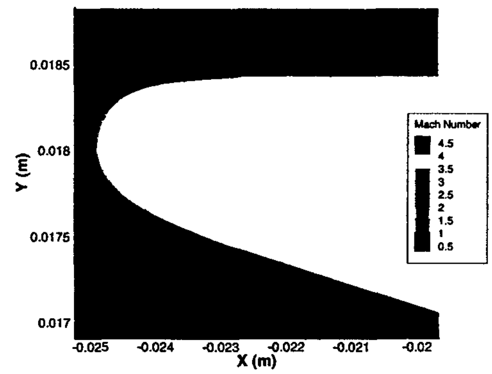

Fig. 13 Mach number contours (300 psia)

The wall shear stress values were calculated for the points around the bleed slot lip of Lip 8. The shear stress plots are shown for the upper and lower sides of the stagnation point separately. Fig. 14 shows the wall shear stress variation for the upper part of the stagnation point at 150 psi with Lip 8, for four different time values. Fig. 15 shows the wall shear stress variation for the lower part of the stagnation point.

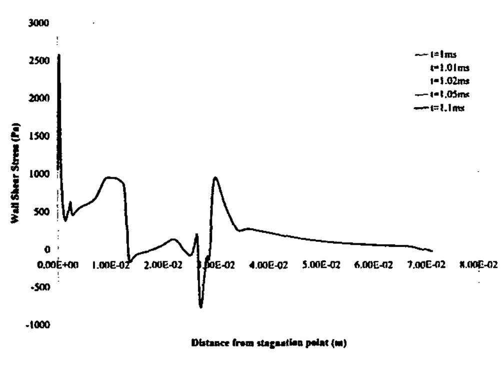

Fig. 14 Shear stress (upper)

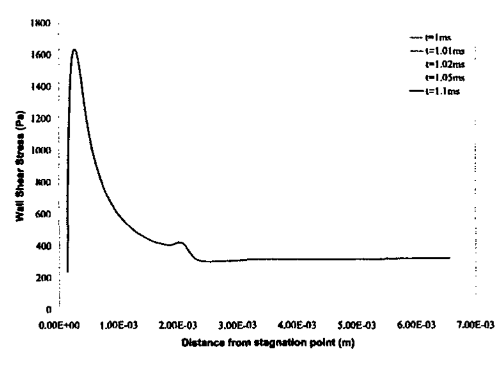

Fig. 15 Shear stress (lower)

As seen in Fig. 14 and Fig. 15, there is no unsteadiness in wall shear stress at 150 psi. The shear stress at the location of the separation bubble which previously existed on the upper side of the bleed lip is high and positive as seen in Fig. 14. The locations where the shear stress is negative in Fig. 14 correspond to the separation bubble on the corner of bleed slot.

As seen in Table 1, the separation bubbles on both the main flow and the bleed flow sides of the bleed lip were eliminated with Lip 8 geometry up to a stagnation pressure of 300 psi.

Table 1. Separation Bubble Lengths

Geometry	Stagnation pressure (psi)	Lsep (main flow) (mm)	Lsep(bleed flow) (mm)
Original lip	14	0.65	2.75
Lip 8	50	0	0
Lip 8	150	0	0
Lip 8	300	0	0

4. CONCLUSIONS

The bleed slot lip for the Purdue Mach 6 Tunnel was redesigned using detailed laminar Navier-Stokes simulations to eliminate the separation bubbles observed in the original design. The separation bubbles were considered the principal cause of the early transition of the nozzle wall boundary layer that caused noisy flow in the test section at low stagnations pressures. The redesigned bleed slot lip exhibits no separation bubbles on either the bleed flow or main flow sides up to 300 psia.

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7. PERSONNEL

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